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HIGH EXPLOSIVE FIELD TEST OF HARDENED ELECTRICAL GENERATORS

By

R. S. Chapler and J. M. Stephenson

May 1971

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INTRODUCTION

Objective

Diesel engine driven electrical generators used to provide emergency or standby power for lighting, communications and life-support systems in hardened Naval shore facilities must themselves be protected from destruction by air blast and/or ground shock. The primary objective of the work reported here was to determine the effectiveness of minimal hardening techniques for protection of generator sets against air blast and ground shock at overpressures of 100 psi. Secondary objectives were to determine the air blast effect on the quality of the electrical power and the effectiveness of a two-layer grating in reducing penetration of the dynamic pressure wave into the grate-covered pits in which the generator sets were located. The purpose of the overall effort, which has been pursued at NCEL for several years, is to establish design criteria for hardened generator sets in grate-covered pits to eliminate the use of expensive generator blast-proof vaults in air blast environments up to 100 psi.

Background

Electrical power required for vital communications and life support equipment in certain Naval shore facilities is normally obtained from either private or federal utilities. In the event normal service is interrupted, power is provided by on-site standby electrical generators. In the event of nuclear attack, it is probable that commercial power lines would be destroyed, and that the emergency electrical generating equipment called into service would have to provide continuity of power even when the proximity of the weapon detonation resulted in the emergency generating equipment being subjected to relatively high static and dynamic overpressures.

The survivability of engine driven electrical generating sets in an air blast environment has been the subject of debate for many years. Uncertainty about the overpressure levels required to damage the equipment has led to several types of protective construction ranging from expensive generator vaults which completely exclude the blast to relatively simple revetments which provide only minimal protection. During Operation PLUMBOB[1], three gasoline engine driven generator sets were located in grate-covered pits, one at the 100 psi overpressure level and two at the 60 psi overpressure level. These generator sets were not running during the test nor was any instrumentation installed. The test results were inconclusive; however, the damage was not catastrophic and recommendations were made that further tests be conducted with fully instrumented diesel engine generators.

In subsequent tests at NCEL, the intake and exhaust ports of an operating diesel engine were subjected to shock tube generated air blasts ranging from 10 to 100 psi.[2] The positive phase duration of these tests was approximately 1.5 seconds. The resultant peak combustion chamber pressure was about 4400 psi, more than 4 times the normal peak pressure. No damage was sustained by the diesel engine, however, the engine speed was reduced by nearly one-third for a short period with the speed returning to a normal level as the overpressure decayed. It was concluded from these tests that these and other engines having similar load carrying capability would tolerate overpressures up to 100 psi applied to both intake and exhaust systems simultaneously.

In 1968, a 500 ton high explosive field test, Operation PRAIRIE FLAT, two 10 kilowatt diesel engine driven generator sets were installed in grate-covered pits and tested at the 100 psi overpressure level.[3] The generator sets were operating prior to the blast but were stopped almost immediately by damage to accessory equipment. The test provided valuable data on the failure modes and identified items which would require hardening to allow the installation to provide continuous electrical power output throughout the blast. The items requiring hardening were the generator control box, the wet-cell starting batteries, the air cleaner, the muffler, the generator end shroud, and the engine oil pan. In addition, to reduce penetration of dynamic pressure wave into the pits, an egg crate type grate was recommended in place of the single layer, parallel-bar grate. It was also found that the standard vibration isolating engine mounts attenuated the ground shock so that no damage attributable to this phenomenon was detected. It was concluded that no special engine mounts were necessary at this overpressure level.

In July 1970, another 500 ton high explosive field test called Event DIAL PACK was conducted at the Canadian Defence Research Boards, Suffield Experimental Station, Alberta, Canada, and NCEL participated with a test of two minimally hardened generator sets located in grate-covered pits.

TEST PLAN

Two 10 kilowatt diesel engine driven generator sets in grate-covered pits would be subjected to simultaneous air blast and ground shock at a 100 psi overpressure level 420 feet from ground zero, as shown in Figure 1. The blast would result from detonation of a surface-tangent, spherical charge of 500 tons of TNT. The generator sets were to have their longitudinal centerlines oriented such that the first would be parallel to the blast wave front and the second would be perpendicular to the blast wave front. Both generators were to be operating under load during the test. Instrumentation to provide data on the air blast and ground motion environment and on the response of both the engine and the generator output to the environment were to be installed. Hardening of the generator sets was to be restricted to those components damaged in the previous test. No modification to the pit structures was to be made other than that necessary to accommodate a two-layer grate in place of the single-layer grate previously employed. Hardening of the fuel tanks and the engine oil filters was to be identical with that employed previously.

TEST INSTALLATION

Field Construction

Two identical grate-covered pits fabricated of corrugated steel and having two-layer grate covers anchored to a circular reinforced concrete girdle were located 420 feet from ground zero where the predicted overpressure would be about 100 psi. The pits were provided with 8-inch-thick, reinforced concrete floors in which I-beams were embedded to provide anchors for the generator mounting skid as shown in Figure 2. The tops of the pits were located 2 inches above the existing grade and the pits were located 18 feet from center to center. The completed pit installation is shown in Figure 3.

Generator Modification

Modification of the generator sets was done at NCEL. After a study of the damage suffered in the Operation PRAIRIE FLAT test, the following steps were taken to harden the two commercial generator sets:

(a) The sheet-metal, electrical-control box mounted atop the generator was removed and replaced by a steel junction box which would prevent damage to the electrical cables extending from the alternator. A new control box, shown in Figure 4, constructed of 3/16" mild steel sheet, was provided to house the critical electrical control components including a pair of wet-cell storage batteries. This box, shown in Figure 4, was provided with several rows of 1/2" diameter holes to allow for necessary ventilation and to permit some pressure equalization. Previous tests indicated that damage to the control box and its components was due to a combination of static and dynamic overpressures which both crushed and battered the thin sheet metal box with resultant damage to vital internal parts. The new box, when anchored to the pit wall, was designed to be strong enough to resist the attenuated dynamic pressure and, due to pressure equalization provided by the small ventilation holes, was to be strong enough to resist crushing by the static overpressure.

(b) The batteries, which suffered sidewall collapse due to overpressure in Operation PRAIRIE FLAT, were placed on the lower portion of the newly designed control box. The batteries were wrapped with polyethylene film, placed in the control box, and cast in place with self-foaming, semi-rigid, ployurethane plastic. Ventilation holes in this lower portion of the control box served to limit the rate of pressure rise in the space and to allow venting of gases evolved during normal operation. Steel angles welded to the outside of the box served to prevent direct entry of the blast wave into the protected space.

(c) A conventional oil-bath type air cleaner is normally provided with the diesel engine but this type of air cleaner suffered extreme damage in the PRAIRIE FLAT test. A new blast-proof air cleaner was designed to protect the engines from excessive amounts of the dust and dirt encountered during the blast. A short section of 10" diameter steel pipe fitted with an automotive type paper air cleaner element, a plug of porous ployurethane foam, a foam support plate of perforated steel, and a thick flame-shield screen are shown disassembled in Figure 5. This air cleaner was bolted on top of the generator frame and connected to the engine intake manifold through flexible connections.

(d) The engine oil pan, of thin sheet metal, was partially collapsed by overpressure in the PRAIRIE FLAT tests. This crushing did not prevent operation of the engine, but the oil level in the pan must be maintained to insure proper operation of the oil pump and to prevent overlubrication of the cylinder walls by excessive splashing of connecting rods into the oil supply. Corrugated steel reinforcing plates were spot welded to the sides and bottom of the oil pan, shown in Figure 6, to prevent crushing.

(e) The engine exhaust silencer or muffler, which was badly damaged in the PRAIRIE FLAT tests, was replaced with a commercially available, heavy duty type and connected to the engine exhaust with a standard weight flexible metallic hose. The muffler was clamped horizontally onto the pit grate-support beam with the exhaust hose running vertically downward to the engine.

(f) The generator end shroud, which was dislodged by the air blast in PRAIRIE FLAT, was secured to the generator and housing with four additional bolts.

(g) Hardened oil filters, fuel tanks and electrical load banks were identical to those employed in the PRAIRIE FLAT test.

Installation

The modified generator sets were installed with their accessory equipment in their protective pits. The generators were bolted to the steel I-beams embedded in the pit floor. The fuel tanks, electrical load banks and control boxes were bolted to the floor and/or wall and electrical power cabling was installed between the generators, load banks, and control boxes. The electrical cabling was securely strapped down. An open faced duct was provided to channel the radiator cooling air upward out of the pit. The orientation of the generator pits was such that in one, the bars in the top grate layer were perpendicular to the blast wave front and the engine-generator longitudinal axis parallel to the blast wave front. This orientation was used in Pit "H". In the other pit, called Pit "S", the top grate layer was parallel to the blast front and the engine-generator longitudinal axis was perpendicular to the blast wave front. In both pits the battery-control box was bolted to the grate support I-beam column to the left of the generator and the fuel tank and load bank were located on the right side of the generator. The grate cover, provided with a removable section for access, was bolted to the top of the pit. With the generators in place the required instrumentation was installed.

Two weeks prior to the test, during a severe thunderstorm, Pit "H" was inundated by water which had soaked through inadequately compacted backfill around the pit walls and poured into the pit through an unsealed, subsurface, instrumentation cable conduit. Soil subsidence around the pit gave clear evidence of inadequate backfill compaction during pit construction. Remedial action consisted of replacement of some control box relays, replacement of the starting batteries, flushing, cleaning and drying of the engine and of the generator. The soil around the top of the pit walls was excavated to a depth of four feet and thoroughly recompacted as it was replaced to preclude further flooding. Upon completion of this unexpected phase of the work, instrumentation and final checkout of the installation were completed.

INSTRUMENTATION

Eleven instrumentation channels were provided at the test side (see Table 1). Five pressure transducers, four velocity gages and two current sensors provided the means by which the free field overpressure, the pits' overpressure, the motion of the pit floors, and the electrical output of the generators were determined.

The free field overpressure transducer was mounted midway between the two pits in a flush surface gage mount anchored in the ground with concrete. The transducer was a shielded diaphragm, semiconductor strain gage type specially designed for measurement of blast phenomena. The transducer was calibrated in-place by using a precision pneumatic calibrator as the reference pressure source. Preshot system calibration was effected by voltage substitution yielding a pressure equivalent output voltage just prior to and just after detonation of the explosive charge.

The pit overpressure transducers, of the same type as the free field overpressure transducer, were mounted in threaded steel adaptors which, in turn, were welded beneath the grate support beam near the vertical centerline of the pit. These transducers were oriented so that the active diaphragm was perpendicular to the direction of blast wave travel to minimize the effects of dynamic pressures on the measurement. Calibration of these transducers was effected by the same method as that for the free field overpressure transducer.

Table 1. Instrumentation

Gage Number	Measured Function	Gage Location	Gage Type	Calibration Equivalent	Range (maximum)
90PS	free field overpressure	ground surface between pits	semi-conductor strain gage	99.9 psi	110 psi
91P	pit overpressure	beneath grate support beam	semi-conductor strain gage	107.0 psi	70 psi
92P	pit overpressure	beneath grate support beam	semi-conductor strain gage	97.0 psi	70 psi
91PC	combustion chamber pressure	engine cylinder #3, Pit "H"	piezoelectric	---	2500 psi
92PC	combustion chamber pressure	engine cylinder 3#, Pit "S"	piezoelectric	---	2500 psi
91I	current	control box, Pit "H"	current transformer/shunt	25 amps, rms	26 amps, rms
92I	current	control box, Pit "S"	current transformer/shunt	26 amps, rms	26 amps, rms
91VV	velocity	floor, Pit "H"	variable reluctance	5.5 fps	10 fps
92VV	(vertical)	floor, Pit "S"	variable reluctance	5.9 fps	10 fps
91VR	velocity	floor, Pit "H"	variable reluctance	1.02 fps	3 fps
92VR	(radial)	floor, Pit "S"	variable reluctance	1.11 fps	3 fps

Two combustion chamber pressure transducers were installed; one in each of the two engines. These transducers of miniature piezoelectric type were mounted in water-cooled adaptors screwed into the engines' precombustion chamber openings normally fitted with either a blank plug or a glow plug. Output from these transducers, being of very high impedence, made necessary the use of impedance convertors to provide the power amplification needed to transmit the electrical analog pressure signals through the 2200 foot long signal cables to the instrumentation bunker. Mounted within the hardened control box where the required low voltage power was available and where blast protection was available, the impedance convertor received the high impedance transducer output through conduit-protected, ruggedized low-noise coaxial cable. The convertor output was transmitted to the instrumentation bunker throughout surface shielded two conductor cable. Calibration of these combustion chamber pressure transducers was not attempted in the field since the peak pressures in the engine under no-load conditions had previously been measured in the laboratory and was considered to be an adequately accurate reference pressure. No voltage substitution was used to calibrate these two channels of instrumentation.

Motion of the pit floors was measured by means of variable reluctance type velocity gages. Two gages were mounted in each pit; one measuring vertical velocity, the other measuring horizontal velocity radially outward from ground zero. These gages were calibrated by a technique in which gravity was used to produce an impressed gage velocity as a function of time. This "fall-through" technique was used to calibrate the velocity gages just prior to installation. Again, installed system calibration was performed by the voltage substitution method just prior to and after the detonation.

Generator electrical output current for each pit was measured by the combination of an isolating current transformer and a current shunt which produced a low level analog output voltage for transmission through buried shielded cables to the instrumentation bunker. The current transformer shunt combination, located in the hardened control box, was calibrated by measuring generator current and the resultant output voltage after field installation over a range of currents from zero to 25 rms amperes.

The transducer output cables were laid in a common trench 3 feet deep and 2200 feet long. The trench was carefully backfilled with uncompacted soil after each cable's continuity between the pits and the instrumentation bunker was checked. At the subsurface point of cable entry through the pits' walls, electrical conduit fittings were employed to protect the cables from possible damage due to soil-structure interaction.

Signal conditioning, amplification and frequency-modulated magnetic tape recording were used to collect the store data at the NCEL instrumentation bunker.

RESULTS

Final check out of generators, engines, remote starting system and instrumentation was conducted two hours prior to charge detonation and with the engines secured the grate access covers were bolted in place. Fifteen minutes prior to detonation the engines in both pits were started by remote control from the NCEL instrumentation bunker. The generator sets and accessory equipment functioned as planned. The 500 ton TNT charge was detonated in accordance with the test schedule.

Fifteen minutes after the detonation, NCEL personnel entered the blast area and found both generator sets running. As shown in Figure 7, the two-layer grate covers both suffered damage; however, only that of Pit "H" in which the top layer of parallel bars was perpendicular to the direction of blast wave travel was damage serious. Damage to the electrical fuse disconnect box had dislodged one end of a fuse from its clip in Pit "S" disrupting electrical output in one of the three phases, but otherwise the units were operating normally. The extent of this damage can be clearly seen in Figure 8. The concrete girdle to which the grates' periphery was attached was severely cracked. The soil around Pit "H" which had been excavated and recompacted prior to the test suffered little depression due to air blast loading; however, the soil around Pit "S" was found to have been permanently depressed from 6 to 8 inches below the existing ground level. This depression was attributed to improper backfilling of the soil around the pit by the contractor.

Only a small amount of crater ejecta was found on the ground at the pit location, 420 feet from ground zero. Although several large lumps of hard clay were found on the grate covers, these missiles did not appear to have caused the damage observed. The 3/16" x 2" flat bars of which the grates were formed were bound with and welded to a 1/4" x 2" border strip. Welding of the grate bars to the border strip was of very poor quality. Inadequate weld penetration and poor fit both contributed to failure of these welds. Under the high loading imposed by the air blast these welds were broken; about 1/3 of the bars on Pit "H" were found to have been torn loose, The grate cover on Pit "S" in which the top layer of bars was parallel to the direction of blast wave travel suffered only minor permanent bending.

Table 2 gives the results of the post-detonation inspection.

On site reduction of the tape recorded data was made as soon after the detonation as possible to allow determination of the actual blast environment and equipment response. Upon return to NCEL the magnetic tape recorded data were computer processed to produce properly scaled time histories of each of the data channels. Computer processing consisted of analog-to-digital conversion of the raw data, application of appropriate scaling factors determined from pre-test calibration of the transducers and insertion of the data into an existing NCEL computer program. All plotted data were referenced to a time 65 milliseconds after the high explosive charge was detonated. Some values of interest from the recorded data are presented in Table 3.

Table 2. Post Detonation Observations

Component	Pit "H" Long axis of generator pointing toward ground zero	Pit "S" Short axis of generator pointing toward ground zero	Comments and Recommendations
PIT			
Grate	Bars torn loose from top grate layer due to poorly welded and fitted surround	No damage	Good workmanship required to assure adequate strength
Corrugated metal shell	No damage	No damage	Design good
Floor	No damage	No damage	Design good
Concrete girdle	Radial cracks	Radial cracks at grate anchor bolts	Minor damage
Debris	No large ejecta, but air heavily laden with dust and soot	No large ejecta, but air heavily laden with dust and soot	Heavy load placed on engine air cleaner
Backfill	No noticeable depression	Depressed 6 to 8 inches as a result of overpressure on inadequately tamped backfill	Backfill must be tamped to nearly in-situ density of surrounding soil
DIESEL GENERATOR SETS			
Operation	Engine continued to run	Engine continued to run	No serious damage

Continued

Table 2. (Continued)

Component	Pit "H" Long axis of generator pointing toward ground zero	Pit "S" Short axis of generator pointing toward ground zero	Comments and Recommendations
Generator	End shroud slightly bent	No damage	Modified fastening method prevented loss of shroud, heavier gage steel recommended for shroud
Air cleaner	Flame shield screen pushed to rear of chamber, foam plug face scorched	Flame shield screen pushed to side of frame plug	Improved flame shield screen required
Exhaust pipe and silencer	No damage	No damage	Design good, use of heavy duty silencer provides adequate protection
Radiator	Slight dishing of top tank	No damage	Design adequate, tanks must be kept free of coolant
Fan	No damage	No damage	Design adequate
Fan shroud	No damage	No damage	Fan clearance, 1/4" more than standard equipment, proved adequate

Continued

Table 2. (Continued)

Component	Pit "H" Long Axis of generator pointing toward ground zero	Pit "S" Short axis of generator pointing toward ground zero	Comments and Recommendations
Radiator duct	Minor bending	Minor bending	Open faced duct design good.
Fuel system	No damage	No damage	Heavy walled fuel tank adequate to prevent damage
Oil filter	No damage	No damage	Design adequate
Oil pan	Mild crushing at un-reinforced lower edges	Mild crushing at un-reinforced lower edges	Recommended that rein-dorcement be extended to cover corners
Fused disconnect box	Box bent at top	Fuse dislodged from spring clip	Fused disconnect box needs redesign and fuse retaining clamps required
Batteries	No damage	No damage	Design adequate

Table 3. Summary of Recorded Data

Recorded Data	Pit "H"	Pit "S"
Free Field Overpressure	94 psi	
Blast Wave Arrival Time	69.5 msec	
Positive Phase Duration	80 msec	
Overpressure	70 psi	68 psi
Velocity of floor	6.6 fps downward 1.0 fps outward	12.6 fps downward 1.3 fps outward
Combustion Chamber Pressure	2700 psi for 1 cycle	1520 psi for 2 cycles
Electrical Output Current	26 amperes ± 4 amperes	25.5 amperes, pre-shot (loss of power on 1 phase due to dislodged fuse)

The recorded free field overpressure time history, Figure 8, shows that the peak overpressure was 94 psi. The blast wave arrival time of 69.5 milliseconds and the overpressure positive phase duration of 80.5 milliseconds agreed with predictions by the U. S. Technical Director.

The overpressure within Pit "H", shown in Figure 9, indicated that only limited penetration of the initial shock wave occurred. An initial shock wave of only 22.4 psig was followed by a relatively slow increase to a peak pressure of 68.5 psi in 9 milliseconds. The pressure then decayed slowly to atmospheric pressure in 108 milliseconds. Similarly, in Pit "S", the initial penetrating shock wave was 23.5 psig with a rapid rise to 30.3 psig in 0.2 milliseconds. A subsequent slow increase to a peak pressure of 59.9 psig occurred over the next 10.6 milliseconds. Pressure decay of this peak level to atmospheric then occurred over an 88 millisecond period for a positive phase duration of 99 milliseconds.

Time histories of the blast-induced vertical and radially horizontal motions of the pits' floors were determined from the recorded velocity gage outputs. Computer data processing was employed to integrate and differentiate each of the four sets of velocity data to determine the respective displacement and acceleration time histories. These computer processed motion-time histories are included in the Appendix.

The vertical floor velocity in Pit "H", shown in Figure A-1, began increasing in a downward direction 77 milliseconds after detonation and reached a maximum value of 6.64 feet per second downward at 87.5 milliseconds after detonation. A subsequent rebound brought the velocity to zero at 113 milliseconds and reached an upward maximum of 1.63 feet per second at 193 milliseconds. Vertical motion during the following 300 milliseconds consisted of low magnitude oscillation; i.e., less than 0.5 feet per second. The vertical floor displacement determined by integration of the velocity data and plotted in Figure A-2 was 1.28 inches downward occurring 113 milliseconds after detonation. The maximum downward acceleration determined by differentiation of the velocity data and plotted in Figure A-3 was 43.7 g's downward occurring 30.5 milliseconds after detonation.

The vertical velocity time history in Pit "S", shown in Figure A-4, indicated a downward velocity beginning at 79.5 milliseconds after detonation and reaching a maximum value of 12.63 feet per second at 88 milliseconds. Rebound resulted in a return to zero at 115.5 milliseconds and a peak upward velocity of 2.20 feet per second at 183 milliseconds. Subsequent motion consisted of low magnitude oscillations; i.e., less than 0.5 feet per second. Integration of the velocity data yielded the results plotted in Figure A-5 and showed a maximum downward displacement of 2.24 inches occurring 115.5 milliseconds after detonation and an upward rebound resulting in a displacement of 0.65 inches at about 568 milliseconds after detonation. Vertical acceleration in Pit "S" plotted in Figure A-6 determined by differentiation of the velocity data attained a downward maximum of 73.9 g's 82 milliseconds after detonation.

The radially horizontal velocity in Pit "H", shown in Figure A-7, was initially outward beginning at 70 milliseconds after detonation and reached initial peak velocity of 1.03 feet per second at 108.5 milliseconds after detonation. A second peak outward velocity of 1.06 feet per second was observed to occur at 236 milliseconds. Rebound reduced the velocity first to zero at 538 milliseconds and then to an inward maximum of 0.77 feet per second at 732 milliseconds. Subsequent horizontal velocities, limited to less than 0.5 feet per second, continued for more than 2 seconds.

The horizontal displacement, determined by integration of the velocity data, and plotted in Figure A-8, beginning at 70 milliseconds after detonation reached a maximum of 2.06 inches outward at 538.5 milliseconds. Upon rebound, the outward displacement decreased to 0.05 inches at 899 milliseconds and again moved outward to 1.28 inches at 1230 milliseconds. The horizontal acceleration, determined by differentiation of velocity and plotted in Figure A-9, was found to reach an outward maximum of 4.5 g's at 140.5 milliseconds.

In Pit "S" the horizontal floor velocity, shown in Figure A-10, beginning at 70 milliseconds rose to 1.11 feet per second at 83 milliseconds, then sharply dropped to 0.2 feet per second inward at 91 milliseconds. A second maximum outward velocity of 1.3 feet per second was reached at 120.5 milliseconds followed by a slow decrease until the velocity reached an inward maximum of .31 feet per second at 333 milliseconds. The velocity then returned to a maximum outward velocity of 0.25 feet per second at 440 milliseconds and then decreased slowly to reach another maximum inward velocity of 1.30 feet per second at 722 milliseconds. A fourth maximum outward velocity of 0.85 inches occurred at 1015.5 milliseconds. Subsequent horizontal motion consisted of decaying oscillations of less than 0.5 feet per second for more than 2.5 seconds after detonation.

Horizontal displacement of Pit "S", obtained by integration of the velocity data, and plotted in Figure A-11, beginning at 75 milliseconds increased to a first maximum of 1.77 inches at 262 milliseconds then, following a slight decrease, increased further to a second maximum of 1.87 inches at 515 milliseconds. These maxima were followed by an inward rebound to a point 1.97 inches toward ground zero from the original position at 902 milliseconds after detonation. Subsequent displacement was reduced to nearly zero at 1250 milliseconds.

Horizontal acceleration of Pit "S", plotted in Figure A-12, reached an outward maximum of 9.1 g's at 82.5 milliseconds after detonation. The maximum inward acceleration of 8.9 g's occurred at 91 milliseconds after detonation.

Measured peak combustion chamber pressure and engine speed time histories for both pits are shown in Figures 10 and 11. In Pit "H" the peak combustion chamber pressure was about 2700 psig, more than 2.85 times the normal 950 psig. Following the initial peak, combustion chamber peak pressure decayed rapidly to nearly 84% oi normal at 640 milliseconds and then returned to normal at about 910 milliseconds. The engine speed decreased from 1800 rpm to about 1550 rpm in the period from 70 milliseconds to 214 milliseconds. Subsequently, engine speed returned rather slowly to 1800 rpm at 670 milliseconds after detonation. The resultant generator output frequency decreased from 60 cycles per second to 51.8 cycles per second, about 13.7% below normal. In Pit "S" the peak combustion chamber pressure was about 1550 psi, nearly 1.62 times the normal 960 psig. After the initial peak pressure occurred, the subsequent pressures decayed to about 69% of the normal at 760 milliseconds.

After an initial sharp decrease from 1800 rpm to 1630 rpm at 214 milliseconds after detonation, engine speed rose to nearly 4% above normal at 552 milliseconds. Subsequent engine speed varied about the normal 1800 rpm with decaying oscillation of less than 1.5% of the normal speed.

In Pit "H" the generator electrical output current decreased to 84.6% of normal at 180 milliseconds after detonation and returned to normal at 450 milliseconds, as shown in Figure 12. In Pit "S" the generator electrical output current in one phase was found to have stopped at 83.7 milliseconds, as soon as the blast wave had penetrated the pit and dislodged one of the three fuses employed.

DISCUSSION

In the PRAIRIE FLAT test the free field overpressure was not measured in the immediate area of the pits but measurements by others at the same distance from ground zero indicated that the free field overpressure was about 93 psig. For this reason the pits were located 10 feet closer to ground zero in DIAL PACK and a free field overpressure measurement was made close to the pits. The peak pressure of 94 psig was again lower that desired but fell within the ± 10 psi tolerance of the 100 psi prediction by the U. S. Technical Director.[4]

The blast wave arrival time of 69.5 milliseconds was almost exactly as predicted and was 3.5 milliseconds less than that in PRAIRIE FLAT becuase of the shorter distance of ground zero. The maximum pressure recorded in Pit "H" of 68.5 psig was somewhat higher than that for the PRAIRIE FLAT test, but was possibly caused by the failure of the top grate layer. In Pit "S" the peak pressure of 59.9 psig was about the same as the pressure in a similarly oriented pit tested in PRAIRIE FLAT.

Evaluation of the effectiveness of the two-layer grate design is difficult because the items damaged in PRAIRIE FLAT test had been hardened for this test. The principal information gained in this test was that high quality construction must be employed to prevent damage.

The hardening techniques applied to the control box, batteries, air cleaner, oil pan, muffler and generator end shroud provided adequate protection, however, several improvements are recommended. The control box in Pit "S" was located in the pit opposite ground zero and downstream from the blast as in the PRAIRIE FLAT test. The control box with its 3/16 inch plate and pressure equalization holes survived quite satisfactorily, however, the top plate was dished about 1/2 inch. To insure survival in the case of multiple blasts it would be necessary to provide additional support for this plate. The fused disconnect or switch box mounted on the side of the control box would have to be modified to prevent fuse loss. The battery enclosure and foam padding served its intended function and no changes are considered necessary. The air cleaners performed as intended and though found to be quite dirty upon post detonation inspection both paper filter and foam plugs were undamaged. The use of an improved flame shield for the air cleaner is recommended to provide better protection for the foam plugs against the high temperatures encountered during the blast.

The maximum combustion chamber pressures were slightly more than one-half in Pit "H" and one-third in Pit "S" of the 4400 psig measured in laboratory overpressure tests. The short duration of the DIAL PACK overpressure pulse and the blast protection afforded by the hardened air cleaner, muffler and air cleaner are thought to have cuased the reduction in combustion chamber pressures.

In Pit "H" the downward vertical velocities of 6.6 feet per second and in Pit "S" of 12.6 feet per second were much higher than the 4 feet per second experienced in PRAIRIE FLAT. Similarly, the peak outward horizontal velocity of 1.0 feet per second in Pit "H" and 1.1 feet per second in Pit "S" were significantly greater than the 0.7 feet per second of PRAIRIE FLAT. The degree of soil compaction and the moisture content of the soil following the heavy rains preceding the test are thought to have contributed significantly to the greater motion; however, no damage attributed tc ground shock was observed.

Changes in the frequency and current from the generator were greater than would be permitted under the definition of precise power, but would not present serious problems for electrical equipment such as lights, heaters, and pumps used in hardened sites. Loss of a fuse in Pit "S" caused a loss of data for that generator when that phase of the three phase output was interrupted. Redesign of the fused disconnect is recommended to prevent such occurrences.

SUMMARY OF FINDINGS

1. The blast caused minor permanent damage to some generator accessory equipment whereas no damage was atrributable to ground shock. The generators continued to run and to produce electrical power during and after the blast.

2. Damage to the pit structures consisted of minor fractures in the concrete girdle at the top of the pits and of moderately severe damage to the top grate layer of Pit "H".

3. Visual inspection of the generator sites indicated no noticeable difference in blast effects in the two pits.

4. The engine speeds and resultant electrical output frequency decreased significantly during the blast and returned to near normal levels quickly as the blast subsided.

CONCLUSIONS

1. The response of the hardened generator sets to simultaneously applied air blast and ground shock was successfully determined.

2. The effect of ground shock on the generator sets was negligible. In spite of relatively strong ground motion, the lack of damage indicates that the standard vibration isolators provide adequate ground shock isolation.

3. Continuous operation of diesel driven electrical generators can be assured at overpressures to 100 psig if certain blast sensitive equipment such as electrical batteries, air cleaners, fuel tanks, and engine oil pans, and exhaust mufflers are hardened.

4. The two-layer grate covered pit was adequate to provide protection for the equipment from the air blast environment in that both the static and dynamic free field overpressures were significantly attenuated.

RECOMMENDATIONS

1. Grate covered pits should be used to protect diesel-driven electrical generators from overpressures to 100 psi.

2. Hardening of generator set accessory equipments must be provided to allow continuous generation of electrical power. Hardening must be provided for fuel tanks, air cleaners, engine oil pans, electrical controls and batteries. Reinforced sheet metal shrouds must be provided to protect generator brushes from possible displacement by dynamic pressures.

3. Standard vibration-isolating engine mounts should be provided rather than special shock-isolating mounts for adequate protection from ground shock.

4. A special air cleaner having high efficiency and blast tolerance must be provided for diesel engines intended for operation in the dust laden air encountered in an air blast environment.

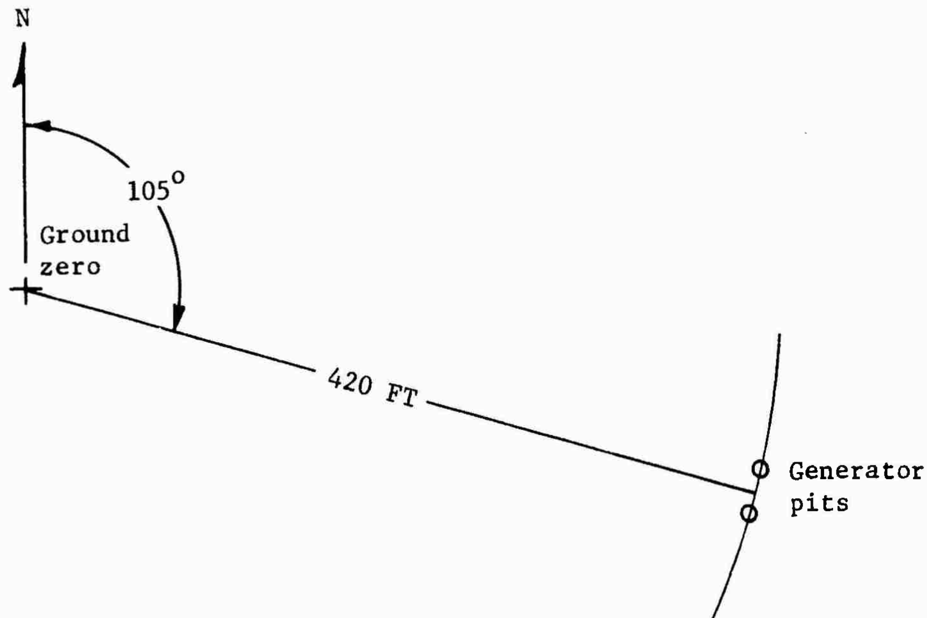

Figure 1. Test site layout.

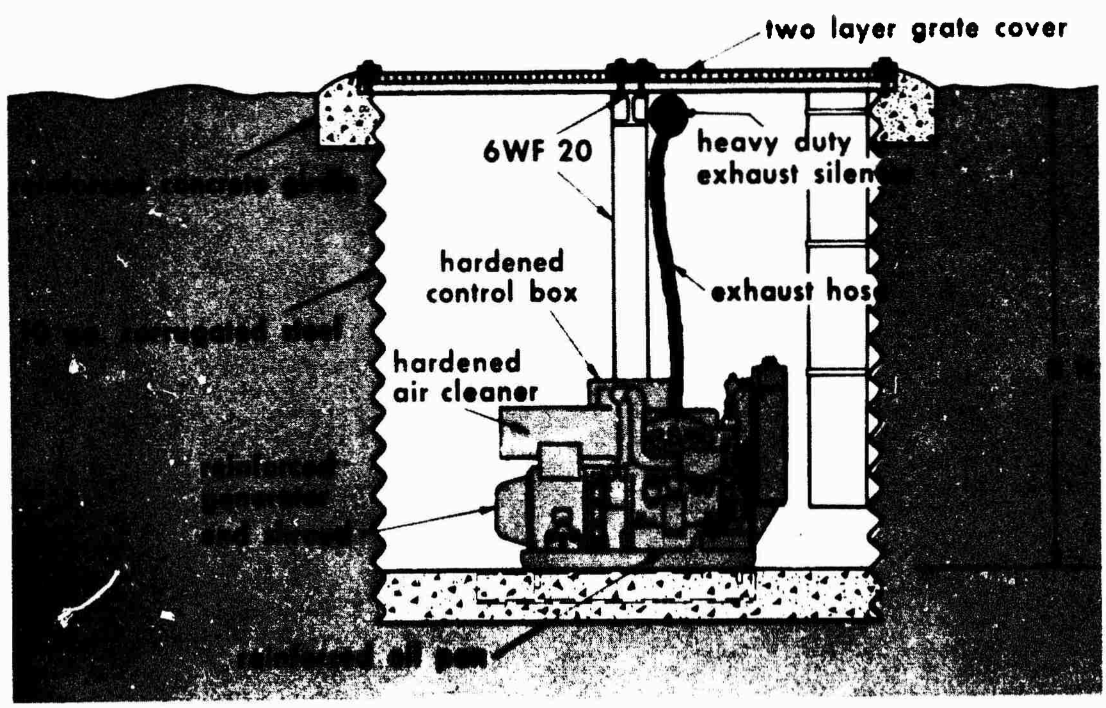

Figure 2. Generator set in pit.

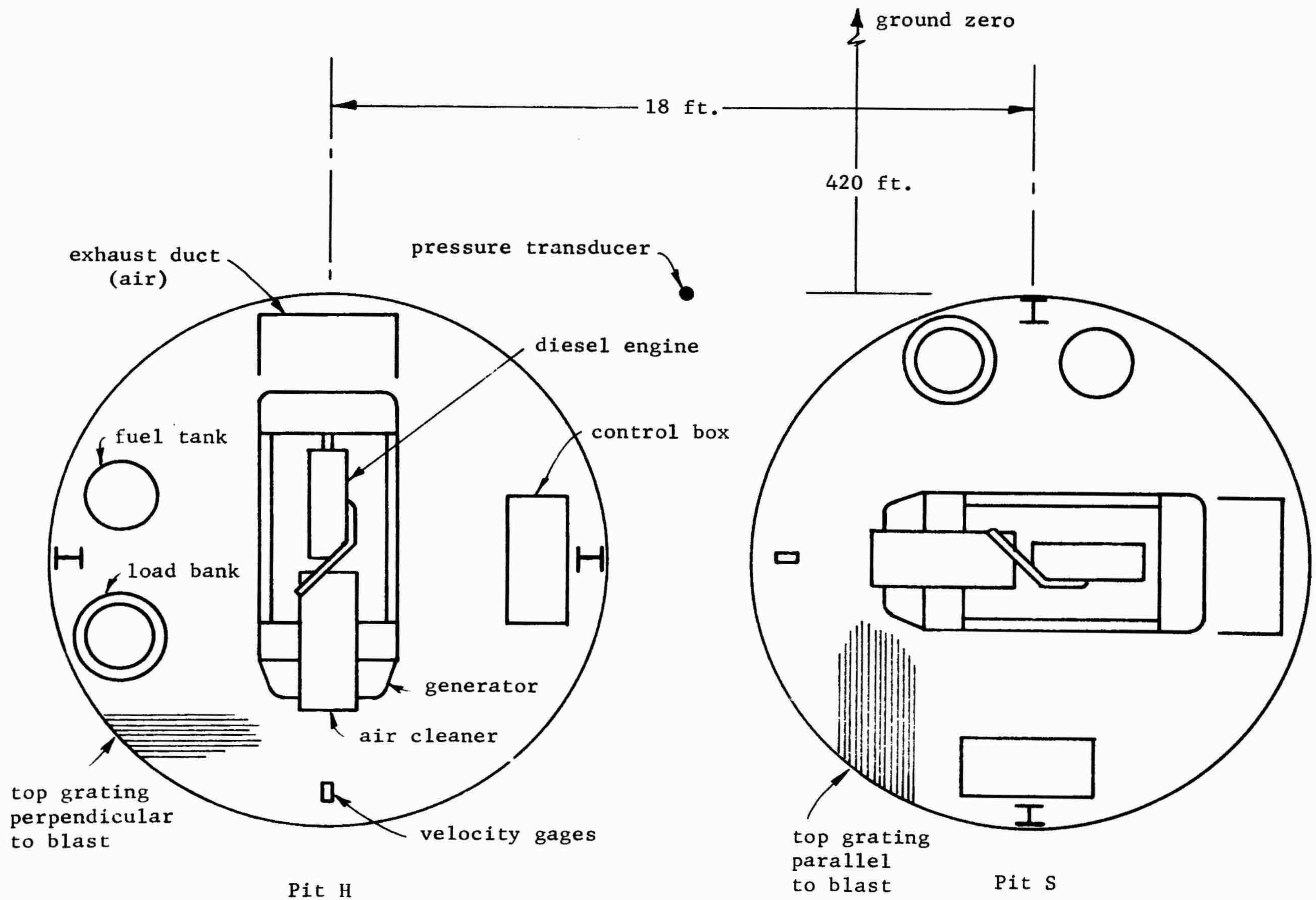

Figure 3. Equipment layout in pits.

Figure 4. Hardened control/battery box.

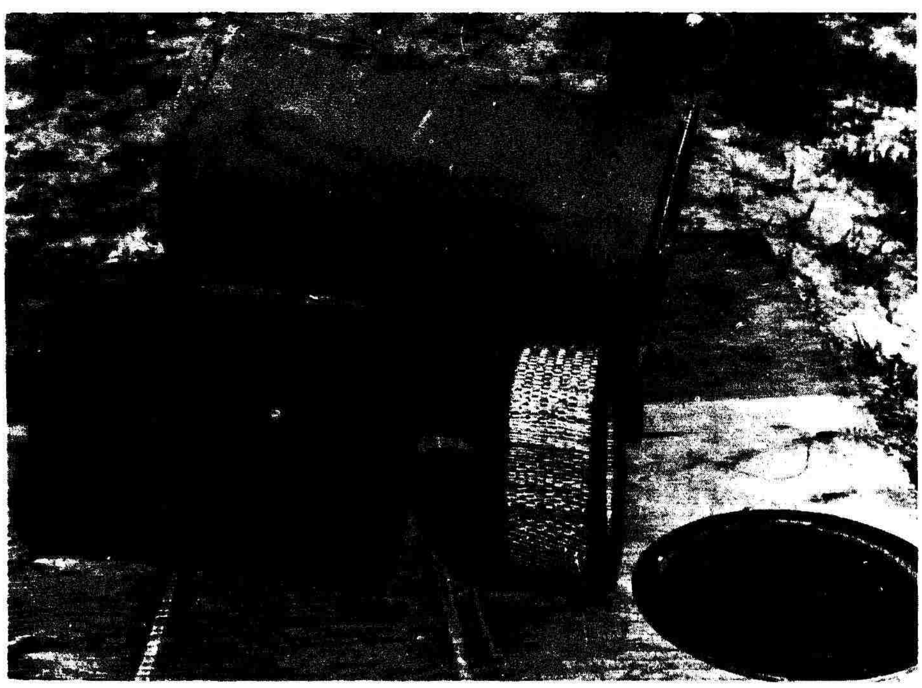

Figure 5. Disassembled hardened air cleaner.

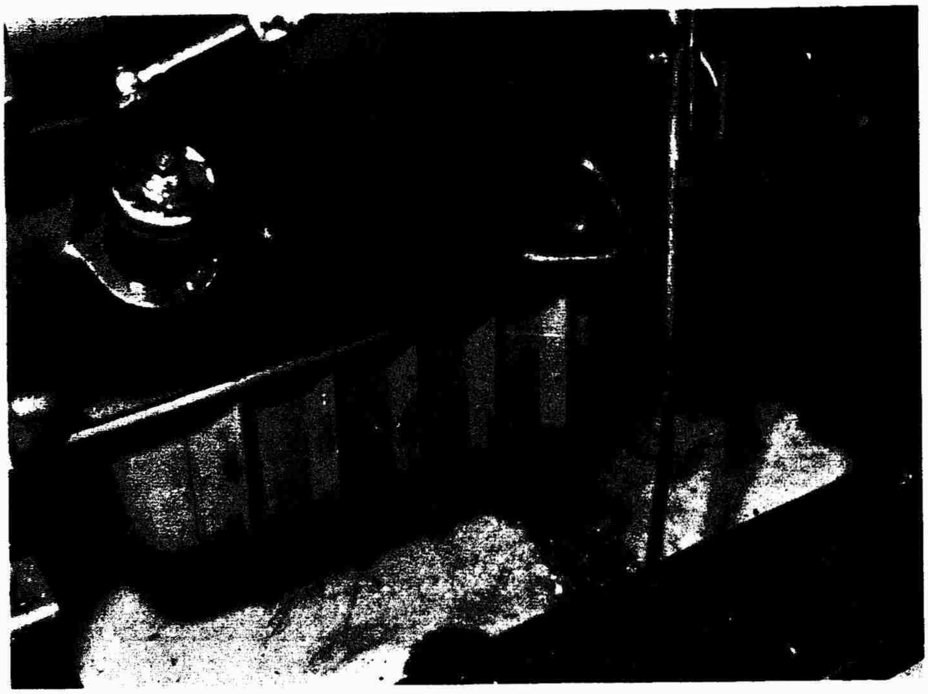

Figure 6. Reinforced engine oil pan.

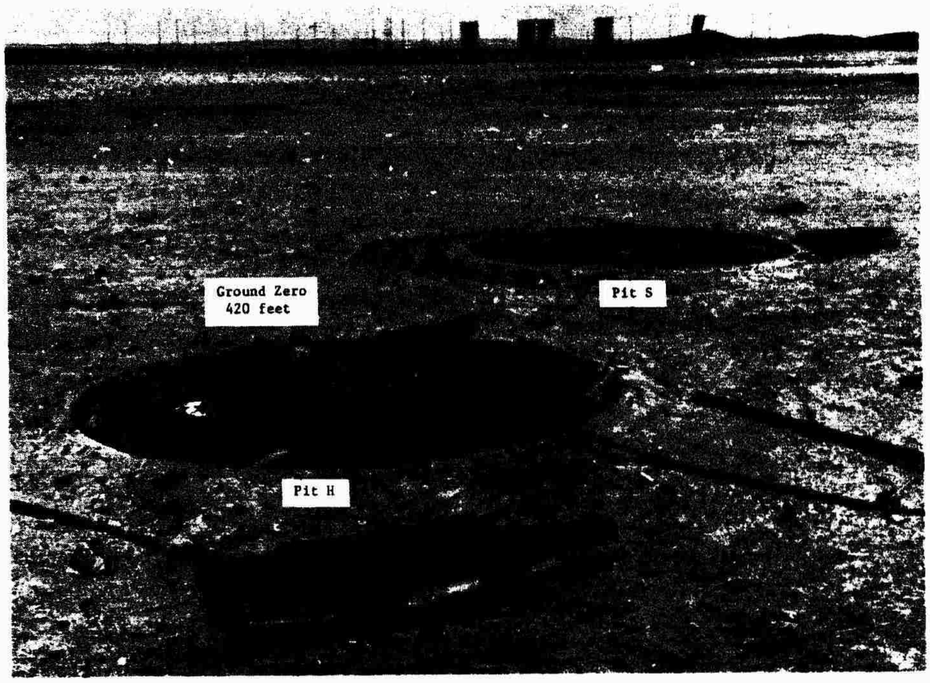

Figure 7. Pits after test.

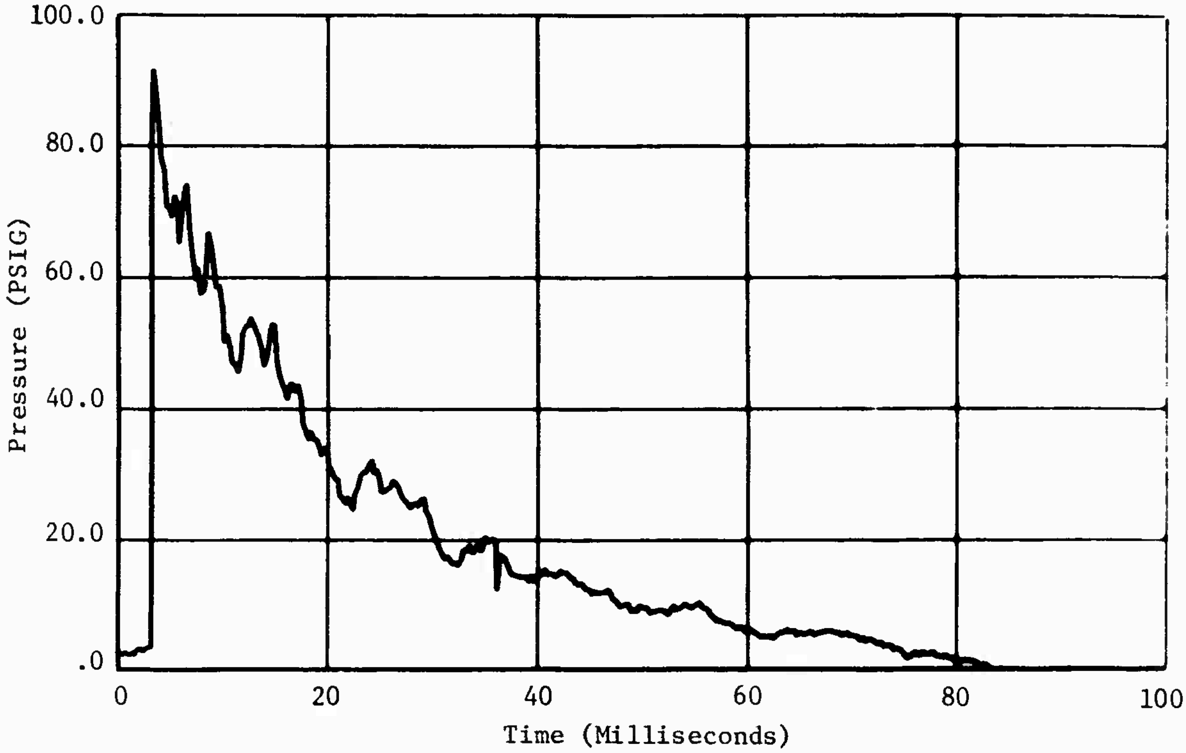

Figure 8. Free field overpressure time history.

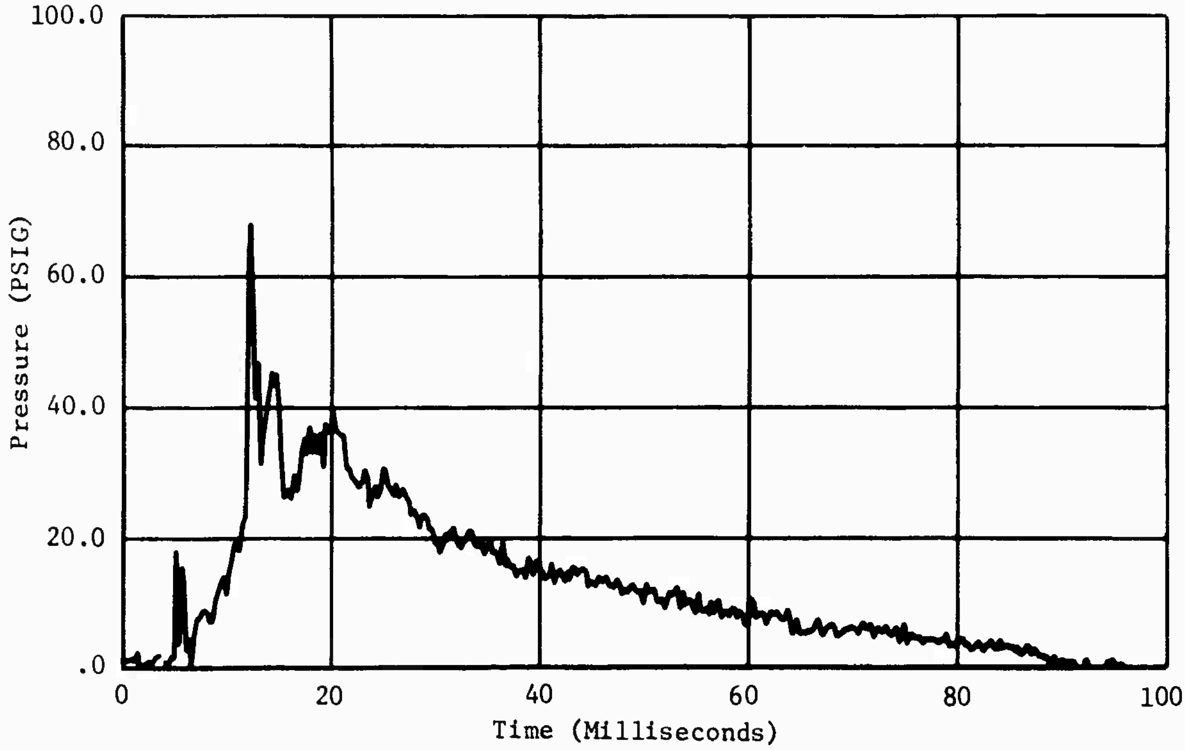

Figure 9. Overpressure time history in Pit H.

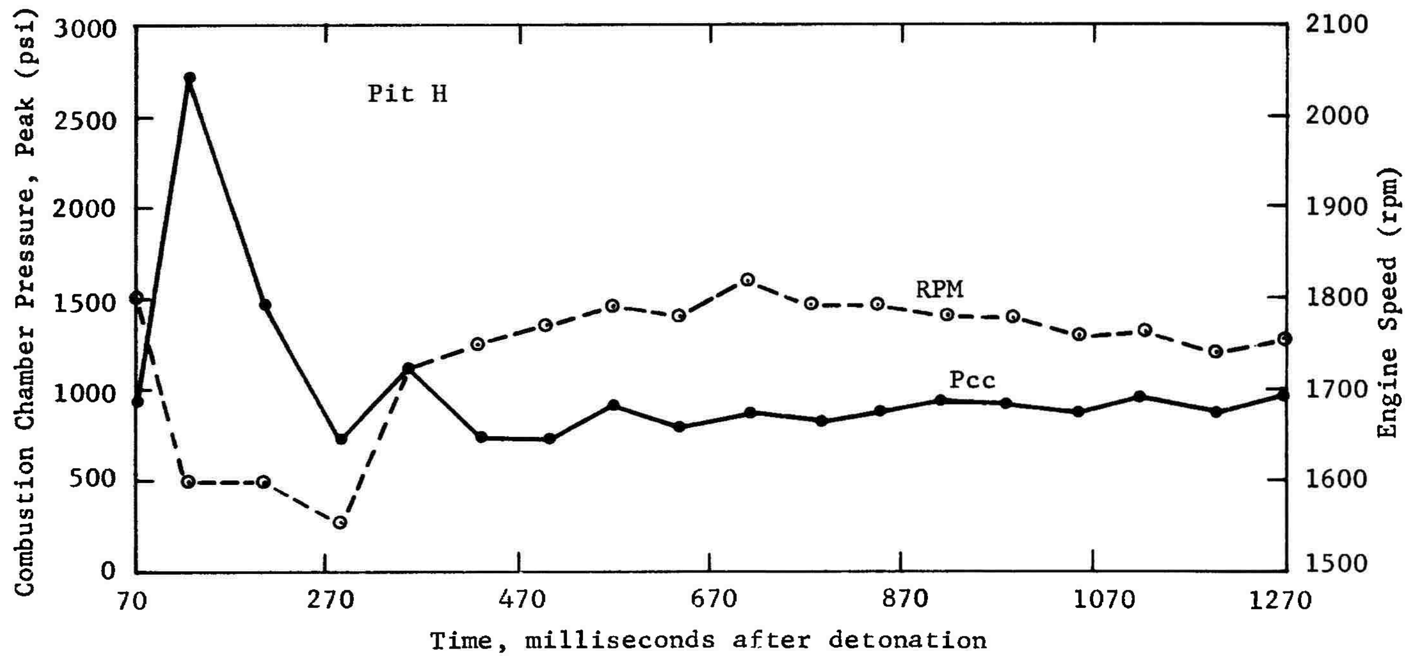

Figure 10. Time histories of engine peak combustion chamber pressures and engine speed for Pit H.

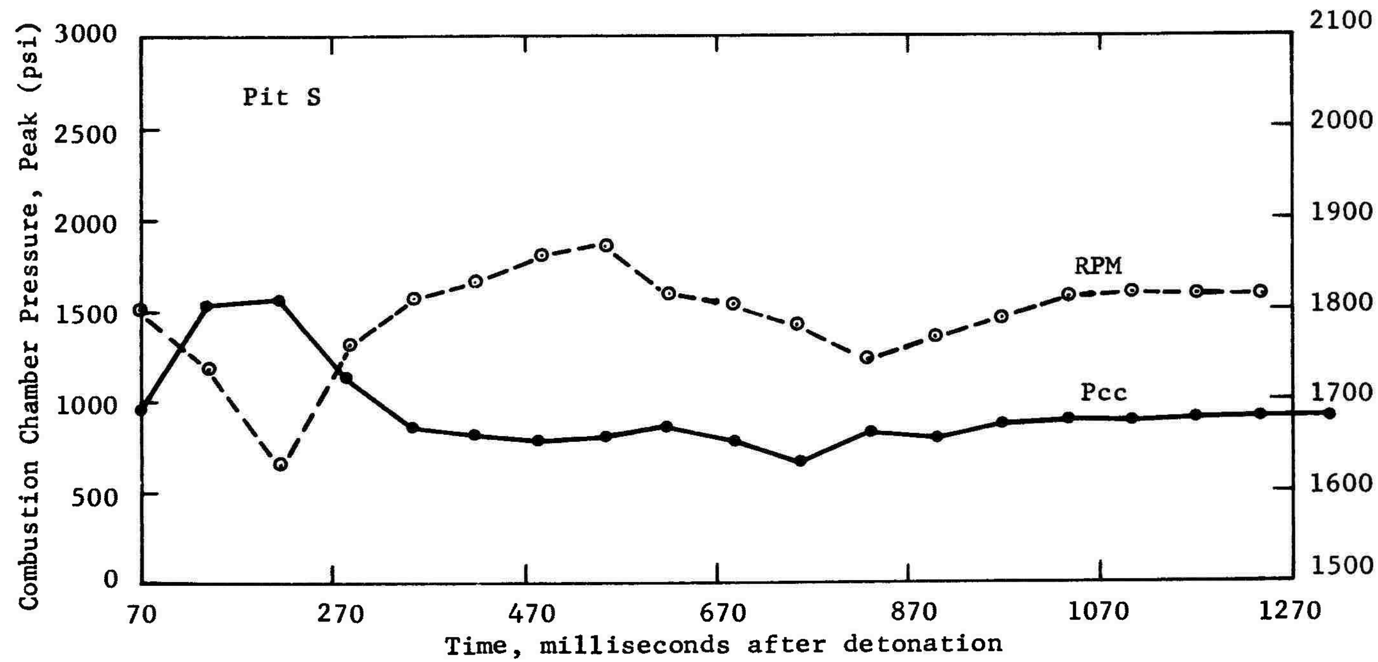

Figure 11. Time histories of engine peak combustion chamber pressures and engine speed for Pit S.

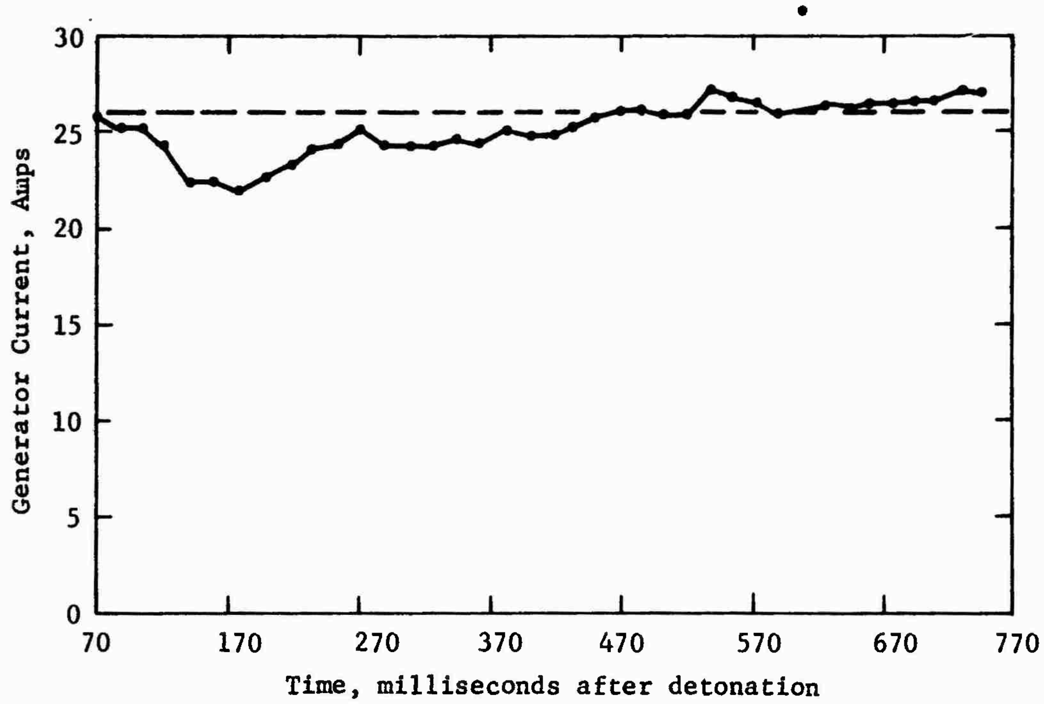

Figure 12. Generator output current in Pit H.

Appendix

COMPUTER PROCESSED GROUND MOTION DATA

Figures included in this appendix are computer-processed time histories of blast-induced motions for each of the four velocity gages employed.

Figure A-1 presents the vertical velocity history of the Pit "H" floor and Figures A-2 and A-3 are the vertical displacement and acceleration histories calculated from the velocity data plotted in Figure A-1.

Figure A-4 presents the vertical velocity history of the Pit "S" floor while Figures A-5 and A-6 are the vertical displacement and acceleration histories calculated from the velocity data plotted in Figure A-4.

Figure A-7 presents the horizontal velocity history of the Pit "H" floor while Figures A-8 and A-9 are the horizontal displacement and acceleration histories calculated from the velocity data plotted in Figure A-7.

Figure A-10 presents the horizontal velocity history of the Pit "S" floor while Figures A-11 and A-12 are the horizontal displacement and acceleration histories claculated from the velocity data plotted in Figure A-10.

In each of the figures, positive values represent upward motion vertically and radially outward motion horizontally. The time in each of the figures is referenced to the time of charge detonation, about 70 milliseconds prior to blast wave arrival at the generator pits' location, 420 feet from ground zero.

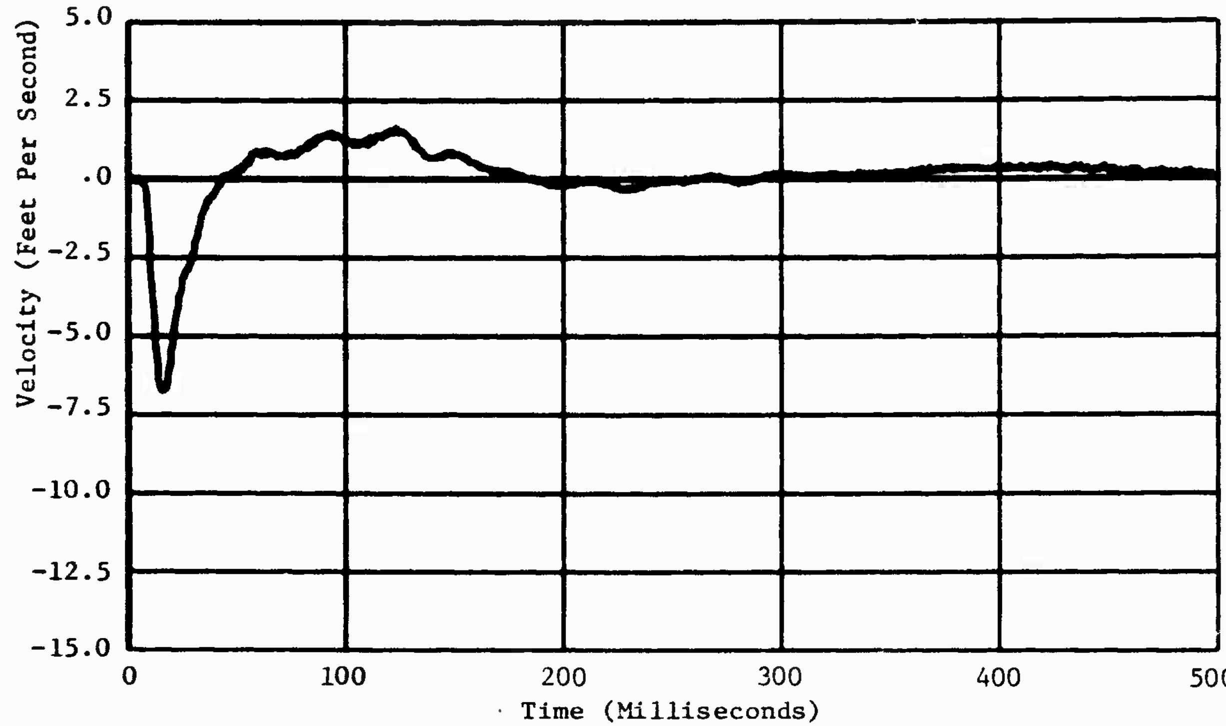

Figure A-1. Vertical velocity of floor in Pit H.

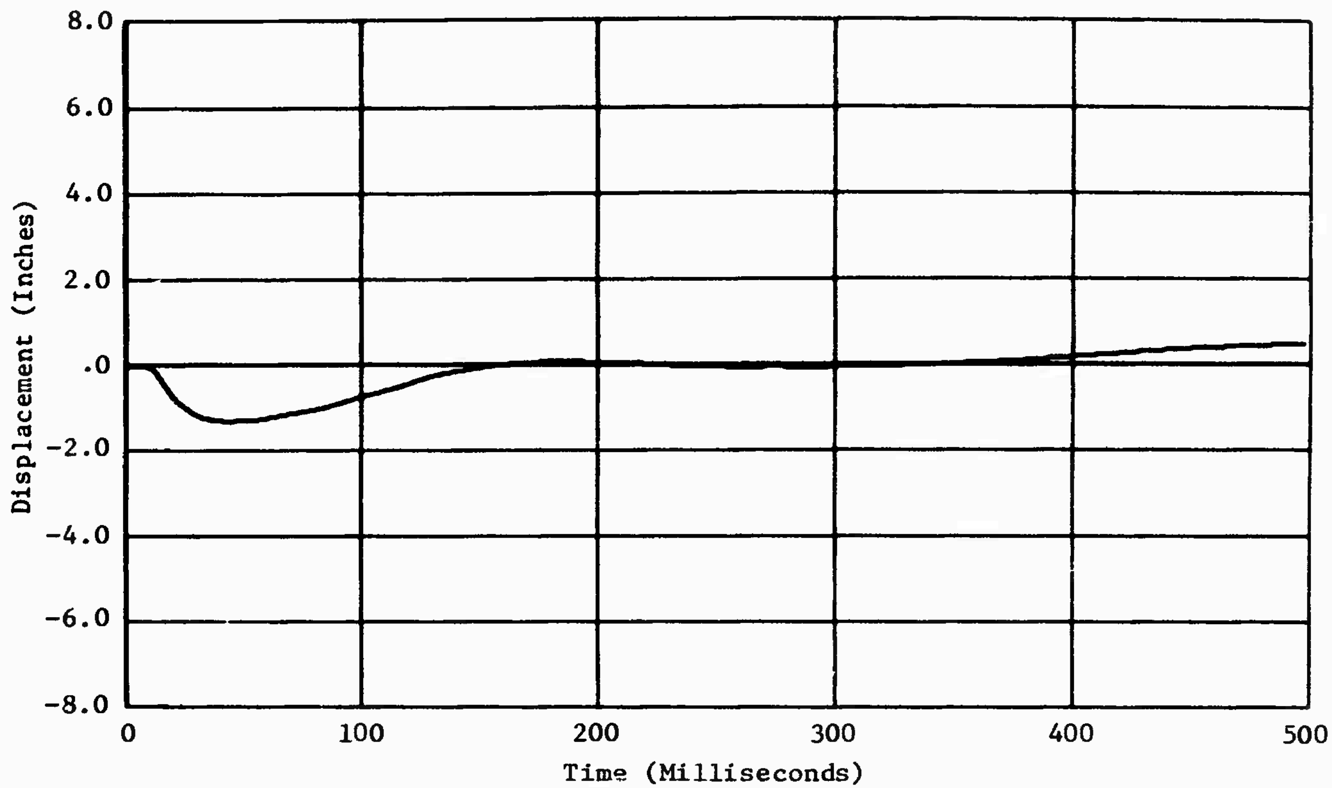

Figure A-2. Vertical displacement of floor in Pit H.

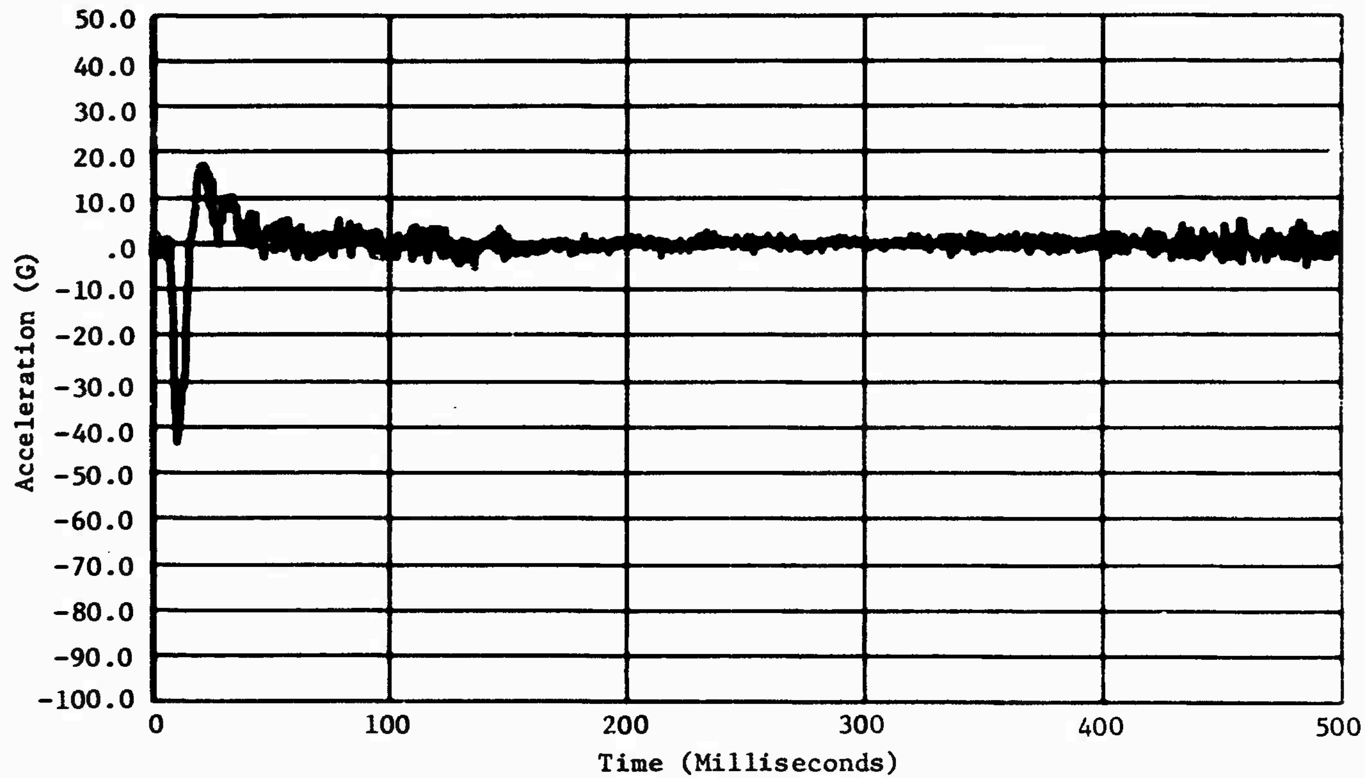

Figure A-3. Vertical acceleration of floor in Pit H.

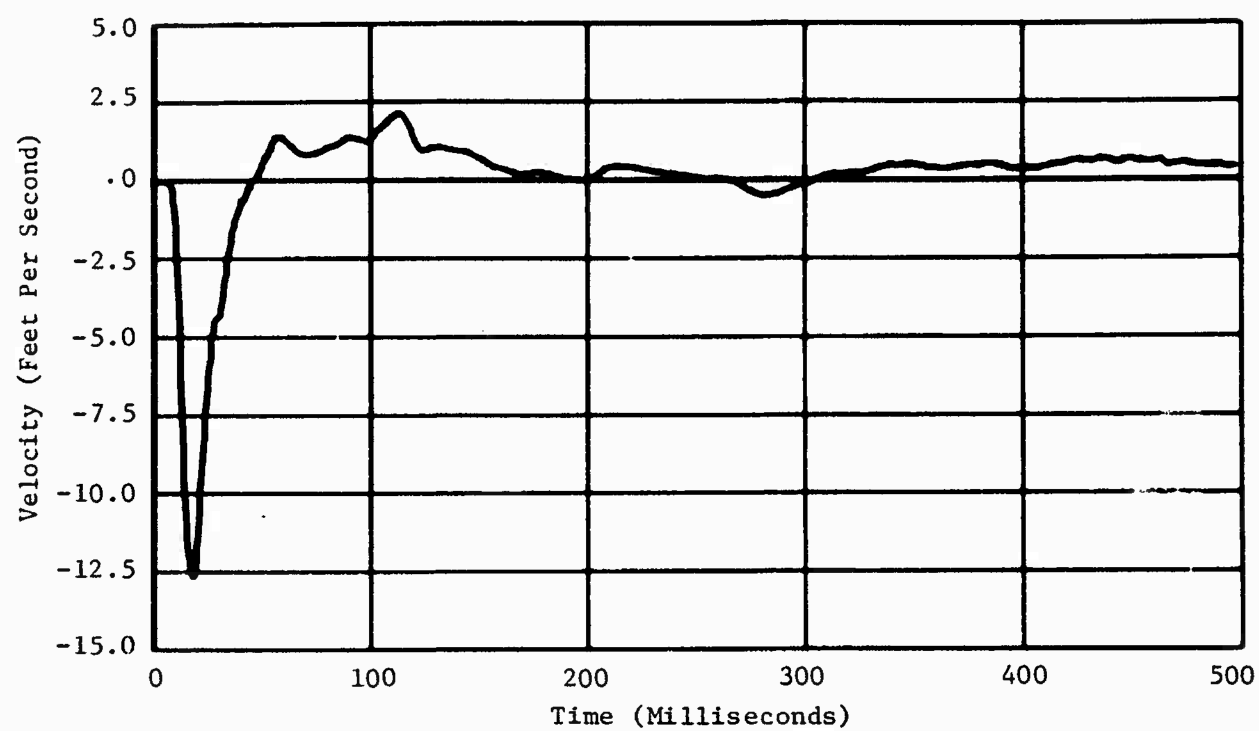

Figure A-4. Vertical velocity of floor in Pit S.

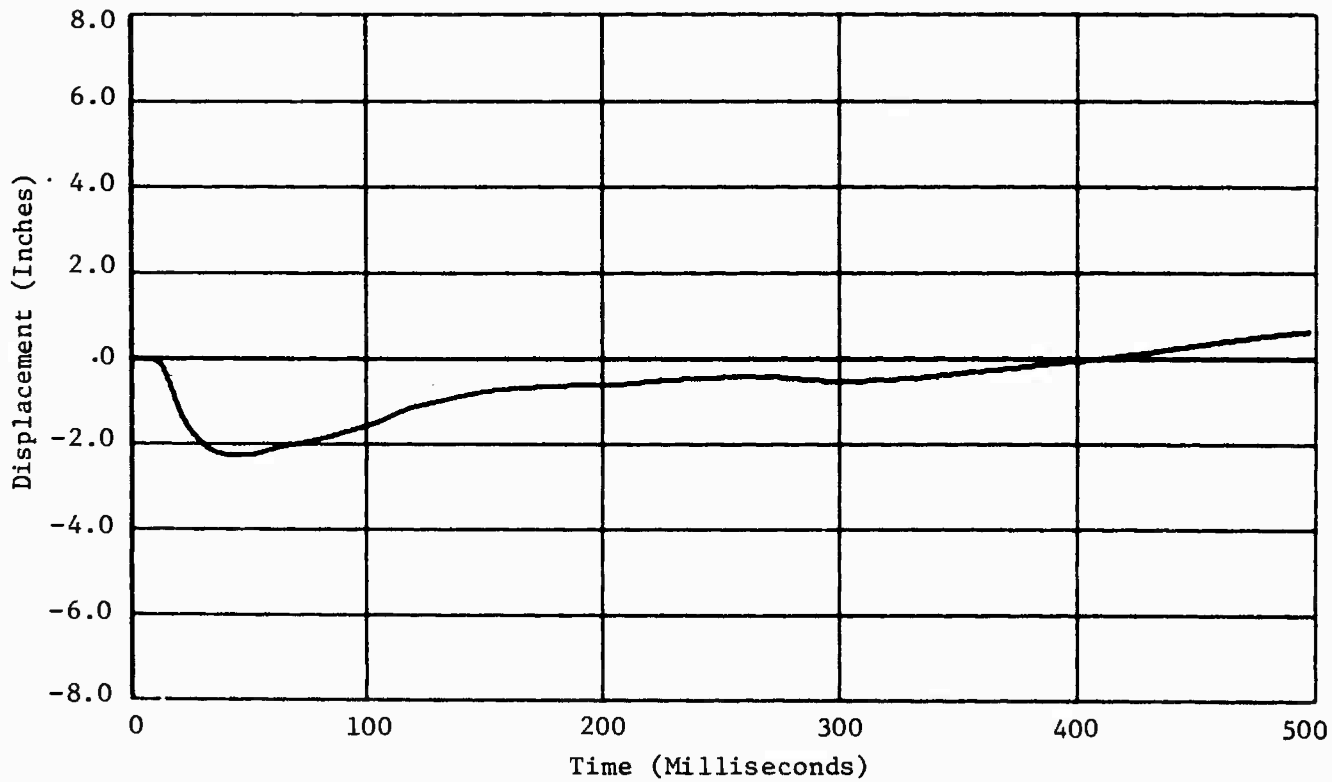

Figure A-5. Vertical displacement of floor in Pit S.

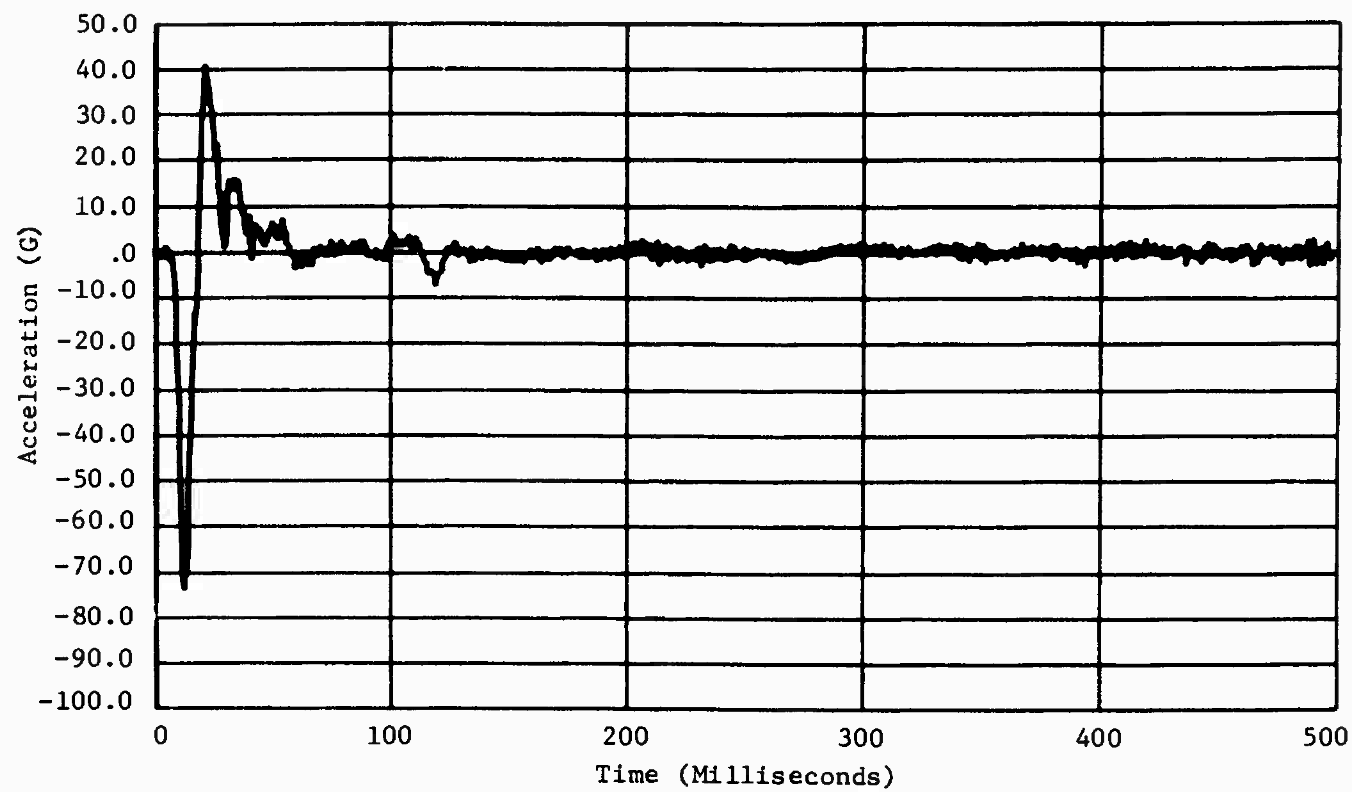

Figure A-6. Vertical acceleration of floor in Pit S.

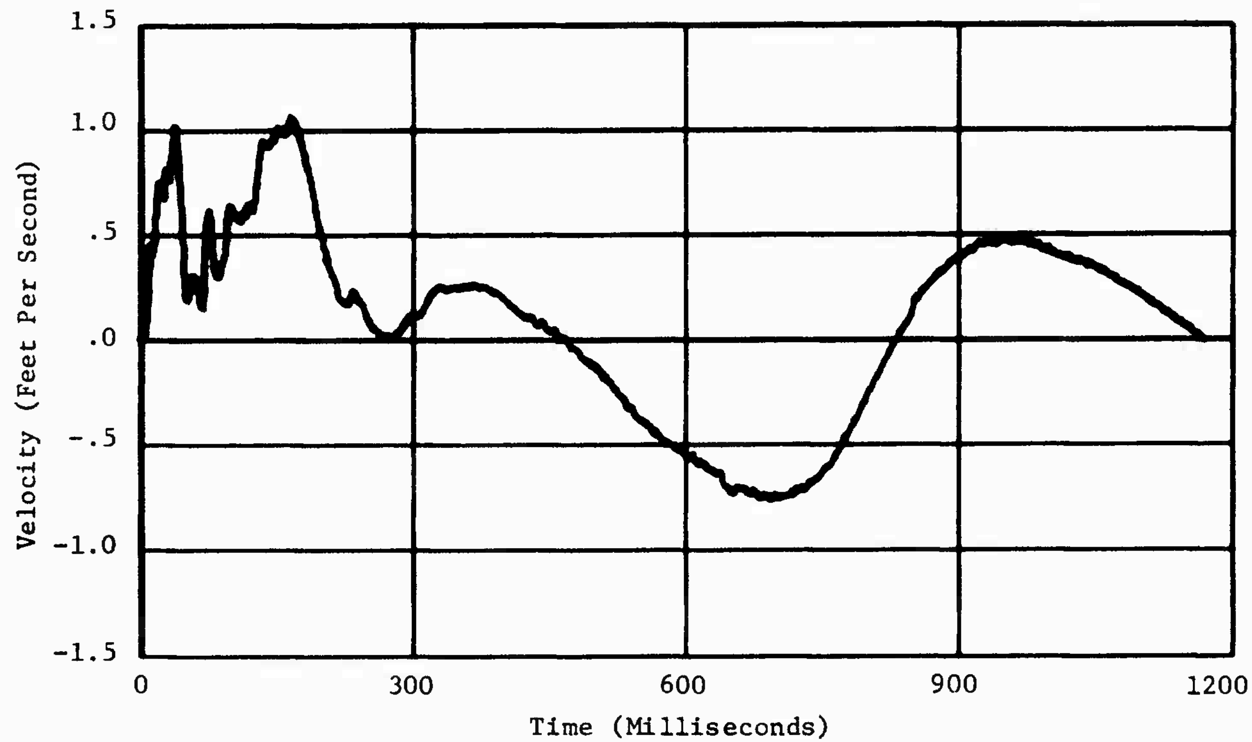

Figure A-7. Horizontal velocity of floor in Pit H.

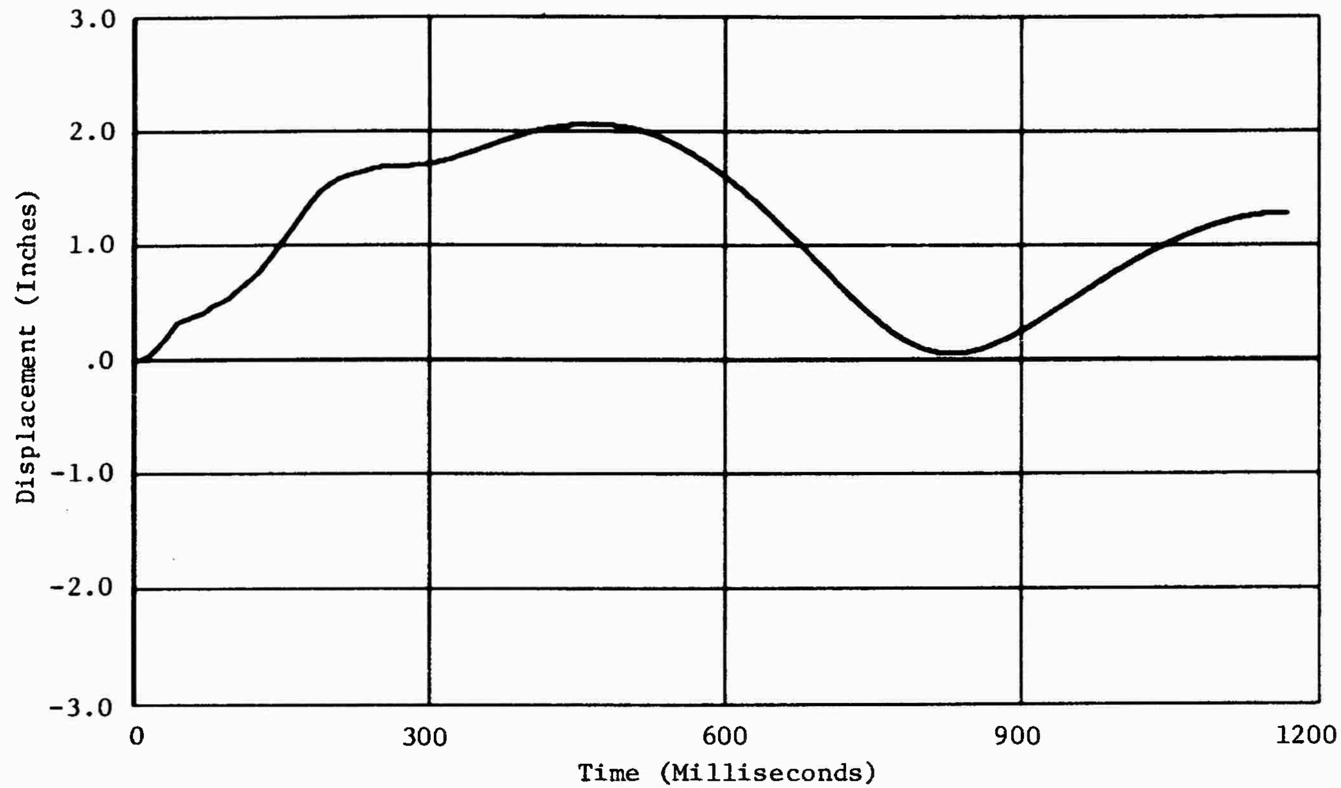

Figure A-8. Horizontal displacement of floor in Pit H.

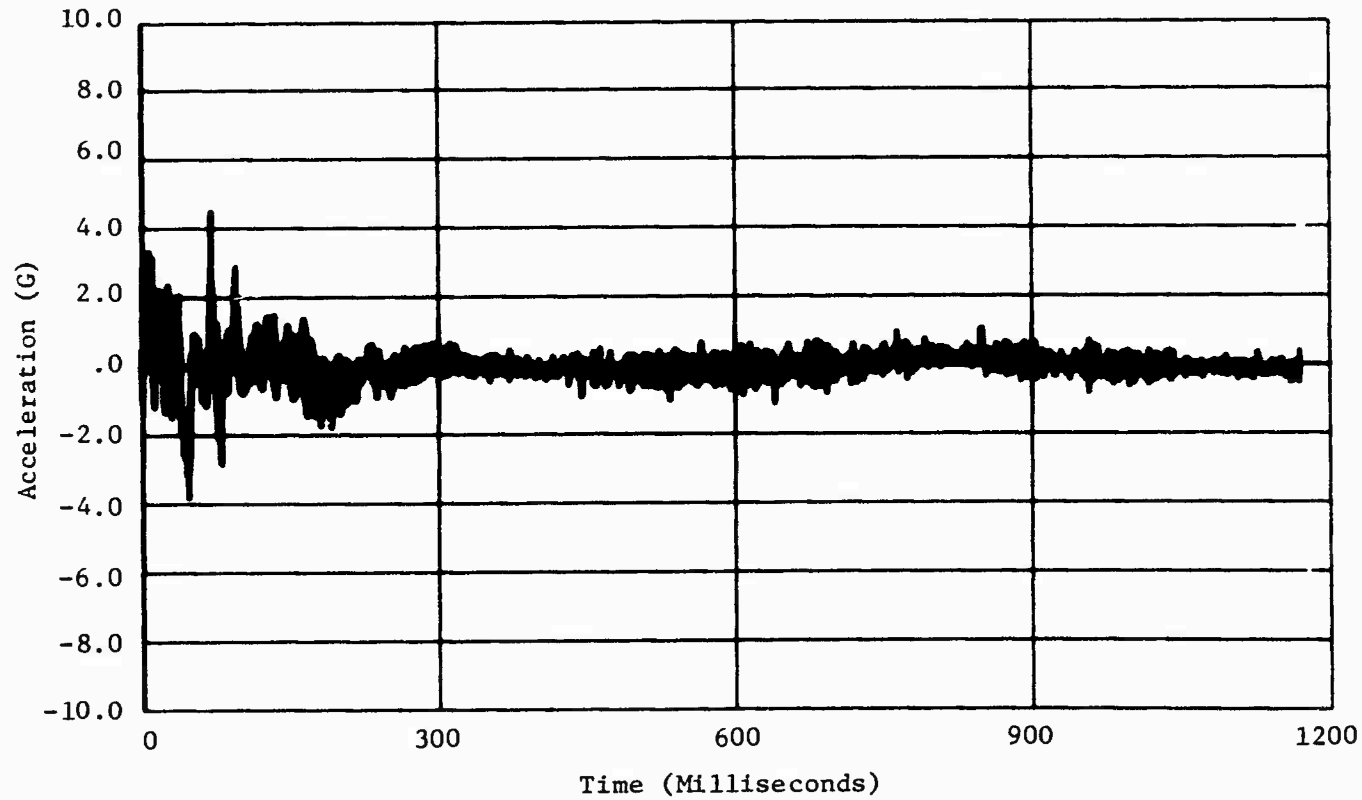

Figure A-9. Horizontal acceleration of floor in Pit H.

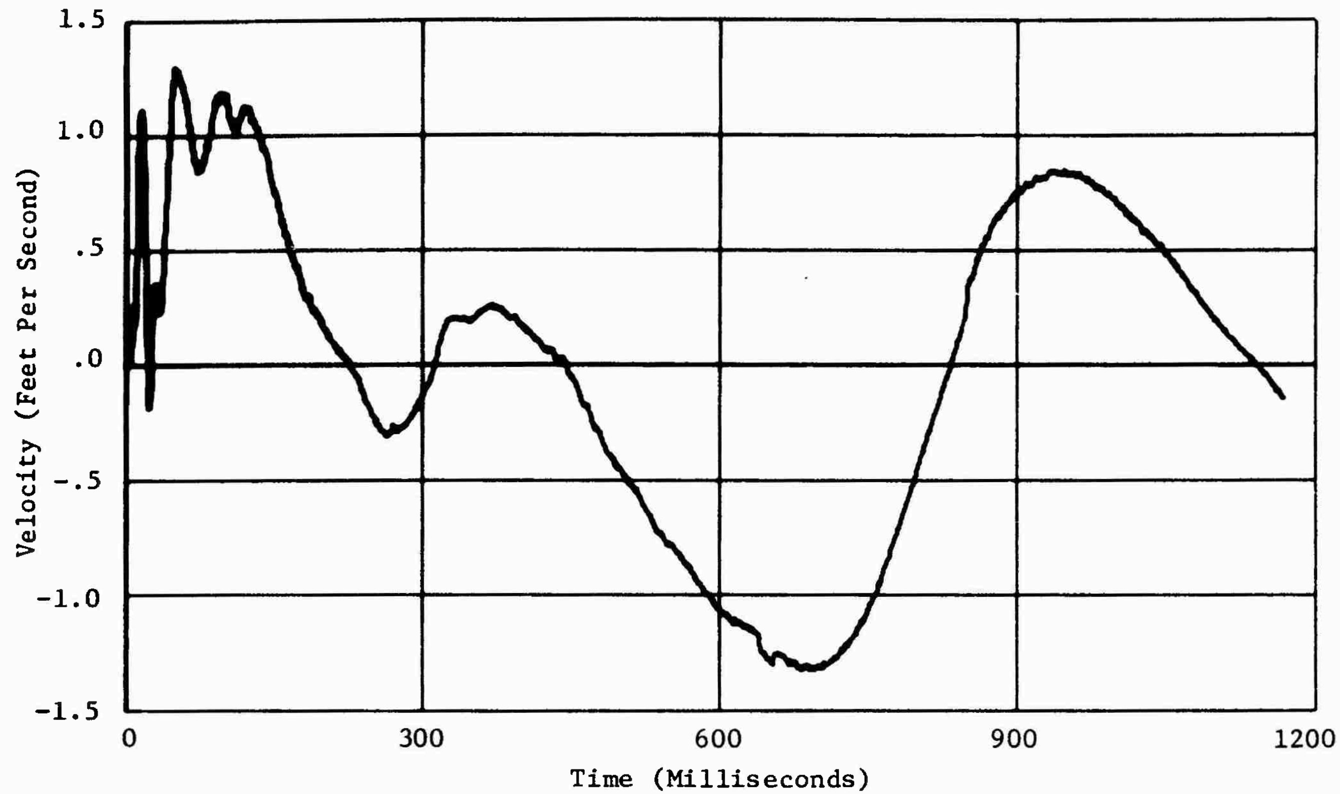

Figure A-10. Horizontal velocity of floor in Pit S.

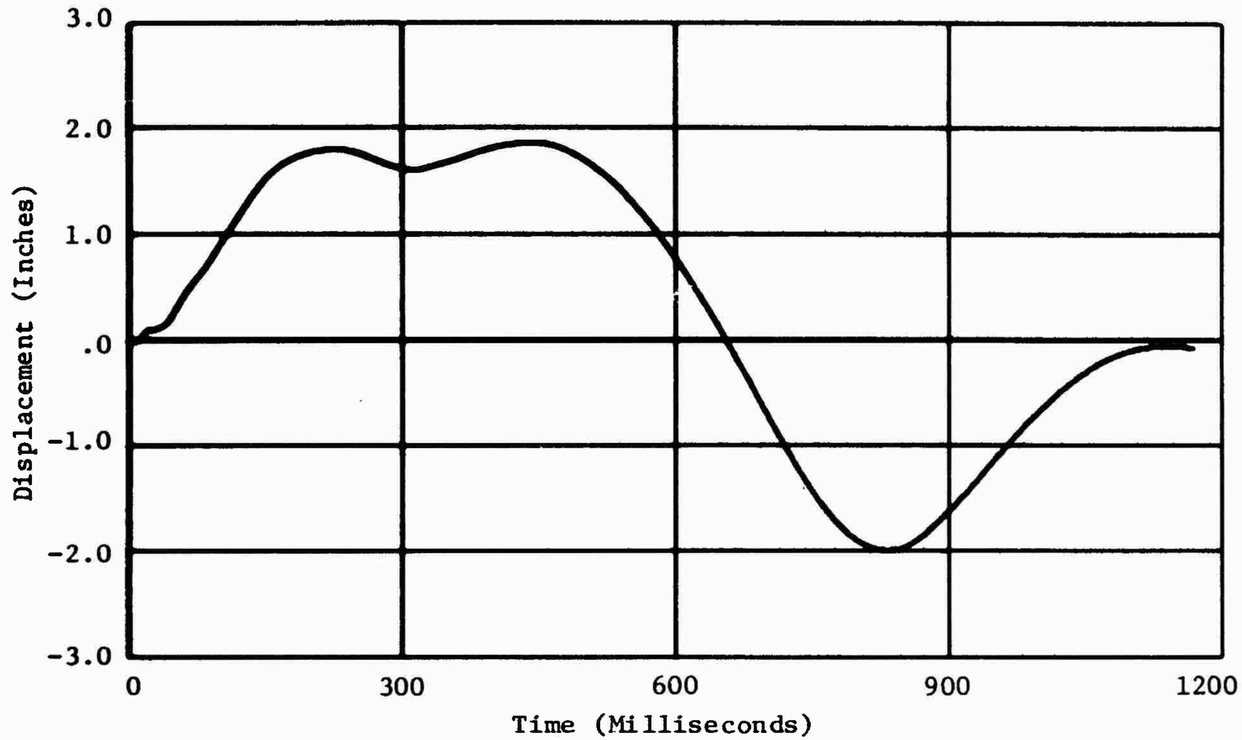

Figure A-11. Horizontal displacement of floor in Pit S.

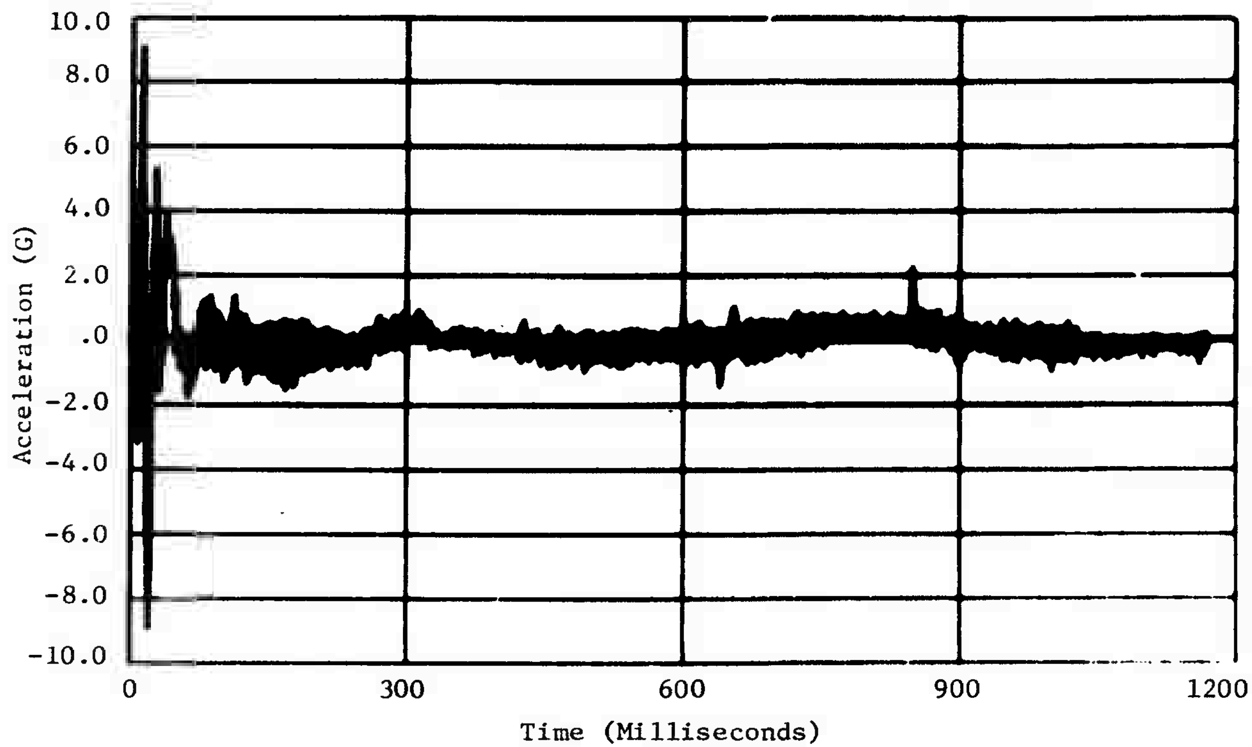

Figure A-12. Horizontal acceleration of floor in Pit S.

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